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Auto-oscillations of a spherical glow discharge in drift-diffusion approximation

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A spherical glow in low-pressure nitrogen for transition from abnormal to Townsend regimes of a spherical discharge has been studied. The model includes non-stationary drift-diffusion equations for electrons and ions coupled with Poisson equation for radial electric field. The auto-oscillations of plasma parameters are obtained.

1. Introduction

A spherical discharge was observed for the first time in 1997 [1]. It was realized in the gap between a central point-like anode and surrounding it cathode.

This paper presents the drift-diffusion numerical study of a spherical glow discharge in nitrogen in a wide range of gas pressures and electric circuit parameters. Oscillating regimes were obtained for transition regimes from abnormal to Townsend discharge forms.

2.Model

A volume spherical discharge was studied in the drift-diffusion approximation. Non-stationary balance equations for electrons and ions were used:

$$\frac{\partial n_e}{\partial t}+\frac{1}{r^2}\frac{\partial (r^2 n_e u_e)}{\partial r}=|n_e u_e| N\alpha_{ion}(E/N)-\beta_{rec} n_e n_i , \quad (1)$$

$$\frac{\partial n_i}{\partial t}+\frac{1}{r^2}\frac{\partial (r^2 n_i u_i)}{\partial r}=|n_e u_e| N\alpha_{ion}(E/N)-\beta_{rec} n_e n_i , \quad (2)$$

where E(r) is the radial course of the electric field, N is gas density, β_{rec} is two-body dissociative recombination coefficient in $e+N_2^+\rightarrow 2N$ collision, α_{ion} is ionization coefficient,. Electron and ion fluxes are presented by drift and diffusion terms:

$$n_e u_e=-\mu_e E n_e - D_e\frac{\partial n_e}{\partial r};\ n_i u_i=\mu_i E n_i - D_i\frac{\partial n_i}{\partial r}, \quad (3)$$

The ionization and diffusion coefficients, electron and ion drift velocities, $W_{e,i}=\mu_{e,i}E$, were taken in the local field approximation. The electric field was obtained from the Poisson equation:

$$-\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial\varphi}{\partial r})=4\pi e(n_i-n_e),\ E(r)=-\frac{\partial\varphi}{\partial r}, \quad (4)$$

Equations (1-4) were solved as the initial problem with boundary conditions for electron and ion fluxes at the cathode and anode. At the initial time step, small electron and ion densities ($\sim 10^4 cm^{-3}$) were set equal to each other, and the Coulomb's distribution was set for the initial radial distribution of the electric field.

In the model, it was assumed that a spherical discharge covers the entire cathode surface (abnormal regime of a glow discharge, subnormal and Townsend discharges).

For the numerical solution of Eqs.(1-4), an implicit finite difference scheme was used. As boundary conditions for the Poisson equation, there was used discharge potential U_{dis}, which was recalculated with the help of the Ohm law: $U_{dc}=U_{dis}-RJ_c$, where U_{ps} is the potential of power supply, R is the active resistance of external electric circuit and J_c is the conduction current at the cathode.

3. Results

Calculations were carried out for different gas pressures ($0.1\le p \le 3.5$ Torr) and parameters of electric circuit (U_{ps}=1-3.5 kV, R=10-25 kΩ). Radius of the central anode was fixed (a=1cm), the radius of the spherical cathode was R_c=12.5 cm. These parameters correspond to conditions of [1] in which spherical stratification of glow discharge was observed.

As a result of numerical calculations the radial distributions of electron, ion, and bulk charge densities, electric field and potential of discharge were obtained.

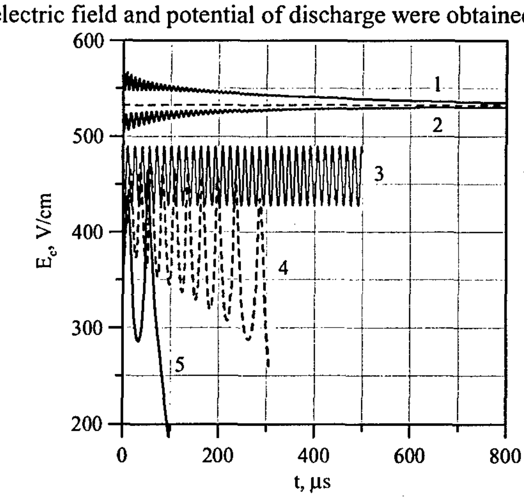

Fig.1. Relaxation (1-2) of electric field at the cathode (R_c=25cm) for different $\Delta U_{ps} = U_{ps}^*(p) - U_{ps}$ and auto-oscillation (3) Decaying regimes (curves 4-5) p=3.5 Torr, and different power supply voltages U_{ps}.

It was found that steady state conditions in abnormal regimes of the spherical glow discharges were formed if sufficient voltage of power supply U_{ps} was applied. In this case, after sudden change U_{ps}, decaying transitional oscillation of all plasma parameters to new stable conditions arose. In Fig.1, the example of such relaxation from two different initial values of power supply is shown. The curves 1 and 2 present transition from U_{ps}=1500V and U_{ps}=1350V to U_{ps}=1400V, correspondently. It is seen that the system (for transitions from different initial states) works out the steady state condition, which corresponds to the new voltage of power supply.

For small supply voltage U_{ps} (smaller than some critical value U_{ps}^*) at a given gas density, a spherical discharge turns into auto-oscillating (self-maintaining) regimes or into decaying modes. For critical value U_{ps}^*, almost sinusoidal oscillation of electric field and conduction current are realized.

It should be stressed that the critical voltage U_{ps}^* is realized only for gas pressures higher than some critical value p* depending on the radius of spherical discharge R_c. For spherical discharge gap R_c=12.5 cm and active resistance of external electric circuit R=20 kΩ, the critical values are $p^* \approx 1.9$ Torr and $U_{ps}^* \approx 800$ V. The oscillation frequency for this case is $f \approx 30$ kHz. For higher gas pressure p=3.5 Torr, $U_{ps}^* \approx 1250$V, f = 60 kHz. This regime is shown in Fig.1 (curve 3).

Frequencies of oscillations correspond to the time of ions move from the center of cathode fall to the cathode surface where they cause secondary emission of electrons.

In Fig.2, radial distributions of electric field for oscillating regime of a spherical discharge at different moments are presented (U_{ps}=1.25kV, p=3.5 Torr). It is seen that the amplitude of electric field changes considerably in every point of discharge gap.

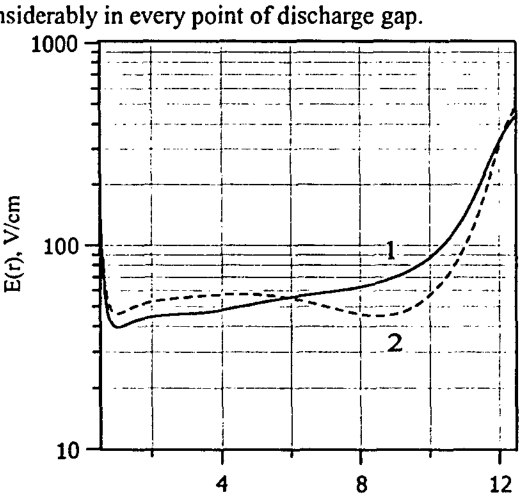

Fig.2. Radial distributions of electric field at two different moments 1 and 2 with interval Δt=12,5 μs, corresponding to anti-phase of oscillation.

It was found that for some regimes with $U_{ps} < U_{ps}^*(p)$ the second oscillating mode appeared. The frequency of this mode is two times smaller than the first one. The amplitude of this additional mode increased with the increase of $\Delta U_{ps} = U_{ps}^*(p) - U_{ps}$. The example of such a bifurcation is presented in Fig.3 for p=4 Torr, U_{ps}^* =1300 V, ΔU_{ps} = 25 V.

The nature of such complex oscillations is connected with the "breathing" of the width of cathode layer.

For larger ΔU_{ps} the oscillating processes become aperiodic, and a discharge turns into the decaying mode (see, Fig.1, curves 4-5).

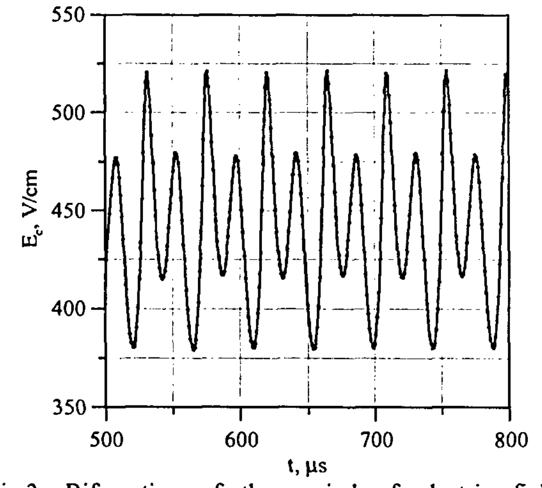

Fig.3. Bifurcation of the period of electric field oscillations $E_c(t)$ at the cathode. The curve is superposition of two modes with frequencies $f_1 \approx 45.5$ kHz, $f_2 \approx 22.7$ kHz, and amplitudes $E_1 \approx 52$ V/cm, $E_2 \approx 27$ V/cm.

4. Conclusions

A DC spherical glow discharge has been studied by means of self-consistent drift-diffusion approximation in a wide range of gas pressure and electric circuit parameters.

In transition regime between abnormal and Townsend regimes of discharge burning, auto-oscillating and decaying modes were obtained. All discharge parameters (conduction current, ion and electron densities, and electric field) oscillated in the whole range of the spherical discharge gap with the frequencies f~10-100 kHz.

The nature of such oscillations is connected with the periodical ionization of molecules in the cathode sheath by electron impact, drift of ions to the cathode surface and secondary emission of electrons from the cathode.

In certain cases, the bifurcation of the main mode of oscillation was obtained. The second oscillating mode with two time smaller frequency appeared due to the doubling of the cathode layer width during one half of the oscillation period.

Similar oscillations have been observed in the experiments (see, for example [2]) in the transition region from Townsend discharge to a glow discharge.

5. References

[1] O.A.Nerushev, S.A.Novopashin, V.V.Radchenko, G.I.Sukhinin, *JETF Letters* **66** (1997) 711.

[2] V.N.Melekhin et al., *Sov. Phys. Tech.* **32** (1987) 274.

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